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Precise orbit determination for a large LEO constellation with inter-satellite links and the measurements from different ground networks: a simulation study

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Abstract

Geodetic applications of Low Earth Orbit (LEO) satellites requires accurate satellite orbits. Instead of using onboard Global Navigation Satellite System observations, this contribution treats the LEO satellite constellation independently, using Inter-Satellite Links and the measurements of different ground networks. Due to geopolitical and geographical reasons, a ground station network cannot be well distributed. We compute the impact of different ground networks (i.e., global networks with different numbers of stations and regional networks in different areas and latitudes) on LEO satellite orbit determination with and without the inter-satellite links. The results are based on a simulated constellation of 90 LEO satellites. We find that the orbits determined using a high latitude network is worse than using a middle or low latitude network. This is because the high latitude network has a poorer geometry even if the availability of satellite measurements is higher than for the other two cases. Also, adding more stations in a regional network shows almost no improvements on the satellite orbits if the number of stations is more than 16. With the help of ISL observations, however, the satellite orbits determined with a small regional network can reach the same accuracy as that with the global network of 60 stations. Furthermore, satellite biases can be well estimated (less than 0.6 mm) and have nearly no impact on satellite orbits. It does thus not matter if they are not physically calibrated for estimating precise orbits.

Keywords: LEO satellite, Orbit determination, Ground station distribution, Inter-satellite link

Introduction

In recent years, a growing interest has been in Low Earth Orbit (LEO) satellites. Many companies announced their plans about building a mega-constellation with hundreds and even thousands of LEO satellites. These satellites mainly serve as a tool to provide global communication and broadband internet (Zhao, 2018; Sheetz, 2019; TASS, 2020; OneWeb, 2021; SpaceX, 2021; Telesat, 2021).

Meanwhile, with these new satellites in space many researchers began to study the applications of these novel constellations, especially in the field of space geodesy. Reid et al. (2018) investigated the possibility of utilizing LEO satellite constellations for navigation. The aspects such as satellite geometry, User Range Error (URE), as well as payload design were discussed. He and Hugentobler (2018), Ge et al. (2020b), Ma et al. (2020), and Zhang et al. (2020) proposed several methods to design such LEO mega-constellations for positioning, either as an independent system or as an enhanced system for the current Global Navigation Satellite System (GNSS). Furthermore, several researchers have studied the positioning performance of LEO-constellation assisted GNSS.

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Compared to a GNSS-only situation, such a combined system can greatly reduce the Precise Point Positioning (PPP) convergence time, and the centimeter level of Signal-in-Space Ranging Error (SiSRE) can be achieved (Li et al., 2018, 2019a). Besides the topics in constellation design and positioning, LEO satellite constellations also show the potential applications in other fields, such as global ionospheric modeling (Ren et al., 2020, 2021) or differential code bias estimation (Li et al., 2021; Yuan et al., 2021).

In view of all applications that have been mentioned so far, precise orbit determination is the foundation. Ground stations take a crucial role in satellite orbit determination. A uniform global distribution with as many stations as possible will be ideal. However, due to geopolitical (e.g., ground segments for BeiDou Navigation Satellite System (BDS)) and geographical (e.g., less stations in the southern hemisphere due to massive waters) reasons, a uniform global distribution cannot be achieved in many circumstances. Some studies about the influence of station distribution on GNSS were conducted. Zhang et al. (2015) compared the orbit accuracy of BeiDou-2 Navigation Satellite System (BDS-2) satellites from a regional (Asia–Pacific) and global ground network. Since the BDS-2 is mainly dominated by Geosynchronous Orbits (GEO) and Inclined Geosynchronous Orbit (IGSO) satellites, they found that the ground stations in this area play a key role in orbit determination. Yang et al. (2020) and Kur and Kalarus (2021) also investigated the change in orbit accuracy with the number of ground stations for BeiDou-3 Navigation Satellite System (BDS-3) and Galileo. In order to conquer this problem, Inter-Satellite Links (ISL) are adopted for Global Positioning System (GPS) and BDS, and proposed for Galileo navigation satellite system (Galileo). ISL was introduced as early as 1980s to serve as additional observations for GPS (Ananda et al., 1984, 1990; Chory et al., 1984). The initial results of GPS Block IIR satellites with ISL show that 3 m URE can be achieved over 75 d of autonomous navigation (Rajan, 2002). Other GNSS, such as GLObal NAvigation Satellite System (GLONASS), Galileo, and BDS, have also planned or already implemented the similar linking system (Fernández, 2011; Ren et al., 2017; Urlichich et al., 2011). The new generation BDS-3 is equipped with Ka-band phased-array antenna, which enables inter-satellite ranging and communication (Yang et al., 2017). By analyzing the data from BDS-3, researchers proved that ISL can not only enable autonomous orbit determination but also improve orbit accuracy by about 50% (Guo et al., 2020; Tang et al., 2018; Yang et al., 2019). The 2nd generation Galileo satellites will also be equipped with K-band ISL technology, which are about to launch earliest in 2024 (European Commission, 2021). Simulation studies show that ISL enhances the geometry of the measurements and results in the better estimation of orbit modelling parameters. The orbit errors can also be reduced (Kur & Kalarus, 2021; Marz et al., 2021; Schlicht et al., 2020).

There are many studies on the orbit determination of GNSS satellites with ground networks and ISL, but little attention has been paid to LEO satellites. Li et al. (2019b) show that with a "4-connected" link topology the three-dimensional (3D) orbit errors of a 60-LEO-satellite constellation are close to 0.1 m if no orbit perturbations are considered in the simulation. When a "all-connected" topology is used, the errors can be reduced by about a factor of two. Michalak et al. (2021) did a full-scale simulation for a new GNSS named Kepler, which is proposed by the German Aerospace Center (DLR). This new system consists of both MEO and LEO satellites. The additional LEO satellites are included to enhance the performance of MEO satellites and possibly reduce the ground segments, which has different applications compared to our simulations. All satellites are equipped with a two-way optical ISL. With this high-low system, the MEO SISRE can be 160 times better than that of the Galileo system. However, the influence of station distribution and number has not been discussed systematically, and the contribution of ISL to the orbit accuracy of LEO satellites as an independent system is also not studied thoroughly. Usually, LEO satellite orbit determination uses the observations from GNSS satellites. With more and more LEO satellites in space, a system that uses the observations from both ground stations and inter-satellite links could also be appealing. Such a system avoids the impact of the errors from the GNSS technique (for instance orbit modelling errors in GNSS satellite products) and ensures its independency. Therefore, we investigate the possibility of such an independent system, and do not use GNSS observations in the estimation.

In this paper, we will systematically analyze the influence of different ground networks and ISL observations on the orbit determination of a large LEO constellation. We introduced the systematic error by using two different atmospheric models and analyzed the bias errors in the simulations. This paper is organized as follows. In "Methodology" section, we introduce the observation models of two types of observations, as well as orbit determination procedure. In "Simulation" section, we show the detailed settings for the simulation and estimation. The results and their discussions are given in "Results" section. We discuss the influence of ground station number and distribution on the orbit accuracy, as well as the benefit of ISL observations. Finally, "Conclusions and outlook" section concludes the paper and gives an outlook.

Methodology

ISL range observation model

Like other ranging observations, the ISL observation model is based on the same principle except that both transmitter and receiver are on satellites. The observation equation of an ISL range can be written as

$$P^{AB} = \rho^{AB} + c\delta t^{B} - c\delta t^{A} + b^{A} + b^{B} + \varepsilon^{AB} \tag{1}$$

where P^{AB} is the pseudorange measured from transmitter satellite A to the receiver satellite B; ρ^{AB} denotes the signal propagation distance; c denotes the speed of light; δt^{B} and δt^{A} are the clock offsets of two satellites; b^{A} and b^{B} represent their biases; and ε^{AB} contains the measurement error and ionosphere effect.

In most of the research, ISL usually works as a two-way or dual one-way link (Li et al., 2019b; Marz et al., 2021; Michalak et al., 2021; Schlicht et al., 2020; Tang et al., 2018; Zhang et al., 2021), which means that each satellite serves as both transmitter and receiver. For this kind of link, the clock offsets between two satellites can be eliminated by transforming the observation equations of both satellites to a common epoch (Tang et al., 2018; Yang et al., 2017). Thus, (1) can be rewritten as

$$D^{AB} = \frac{\rho^{AB} + \rho^{BA}}{2} + b^{A} + b^{B} + \varepsilon^{'}_{AB} \tag{2}$$

where ρ^{AB} and ρ^{BA} represent the propagation distance that the signal travels from satellite A to B and from satellite B to A, respectively, and $\varepsilon^{'}_{AB}$ is the measurement error and ionosphere effect of this observation.

Ground range observation model

The observation of a LEO satellite to a ground station can be written as

$$P_{r}^{s} = \rho_{r}^{s} + c\delta t_{r} - c\delta t^{s} + b_{r} + b^{s} + \varepsilon_{r}^{s} \tag{3}$$

where P_{r}^{s} denotes the measured pseudorange between satellite s and ground station r; ρ_{r}^{s} contains the geometric distance between the satellite and the ground station; δt_{r} and δt^{s} represent the station and satellite clock offset, respectively; b_{r} and b^{s} denote the station bias and the satellite bias as caused by hardware delays; and ε_{r}^{s} is the measurement error. Other effects like tropospheric delay are not considered in this paper. Although they impact the quality of the orbit determination, these errors will not change the discussions and conclusions we made in this paper.

As communication constellations, these LEO satellites should be able to transfer the data by both uplink and downlink. Moreover, in practice, the BDS-3 also has dual one-way link to a ground anchor station. According to Xie et al. (2020), an anchor station is like a virtual satellite on ground and transmits the same signal as a satellite. Then like (2), (3) can be rewritten as

$$D_{r}^{s} = \frac{\rho_{r}^{s} + \rho_{s}^{r}}{2} + b_{r} + b^{s} + \varepsilon^{'s}_{\ r} \tag{4}$$

with the clock offsets eliminated too. ρ_{r}^{s} and ρ_{s}^{r} denote the signal propagation distance of satellite-ground and ground-satellite, respectively. $\varepsilon^{'s}_{r}$ represents the measurement error of this pseudorange observation. Equation (2) and (4) are used as observation models in our simulations.

Simulation

For the LEO satellites a Walker constellation is selected: 900 km, 73°: 90/9/1. To be more specific, the orbit height is 900 km, the orbit inclination is 73° (He & Hugentobler, 2018); the constellation contains 90 satellites, which are distributed in 9 equally spaced orbital planes, and the relative spacing between satellites in adjacent planes is 1. In our simulations, the maximum number of satellites that can be visible at the same epoch varies from 3 for a low latitude station to 7 for a high latitude station.

The link topology of ISL also affects the accuracy of orbit determination. Different link topologies such as "4-connected", "all-connected", "ring", and "open ring" have already been investigated (Kur & Kalarus, 2021; Li et al., 2019b; Schlicht et al., 2020). The "4-connected" topology permanently connecting a satellite to two neighboring satellites in the same orbital plane and the closest satellites in each of the two neighboring orbital planes (Fig. 1) is adopted by Iridium, a well-known LEO communication system (Gvozdjak, 2000; Werner et al., 1995). We also adopt this topology in our experiment. This means that for each satellite, 4 terminals are used for ISL and 1 terminal for ground range. Each terminal has a different bias. For one epoch, each ISL terminal

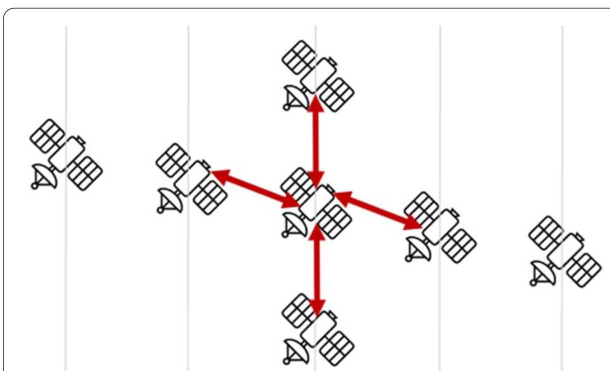

Fig. 1 Illustration of "4-connected" ISL topology

connects to one other satellite, while one ground station can observe several satellites. The minimum and maximum link distance in our experiment is 2 246 km and 5 401 km, respectively.

For a LEO satellite, air drag is the largest non-gravitational perturbation (Montenbruck & Gill, 2000, p. 83). This paper considers this main disturbance. Other perturbations, such as solar radiation pressure and albedo, are not considered since we focus on the impact of distribution and number of ground tracking stations on satellite orbits. All the settings of orbit simulations are given in Table 1.

We use our own software, which is developed based on the open-source space dynamics library Orekit (https://www.orekit.org/). The ground stations are selected from the International GNSS Service (IGS) network and Nevada Geodetic Laboratory (NGL) GPS network. Both types of observations are simulated with white Gaussian noise. Constant satellite specific biases are considered in the simulation. Note that for the same satellite, the bias for ground range observations is different from the bias for ISL observations, since they usually do not share the same antenna. Table 1 also lists the details of the simulation of the measurements. The values are inspired by other simulation studies (Marz et al., 2021; Michalak et al., 2021). Here, we choose 5 mm noise level for ground range measurements to simulate the typical noise level of microwave links of a few millimeters. Since the simulation does not include other effects such as atmospheric delays and multipath, as well as the clocks and ambiguities (take it as pseudorange), we select a slightly larger value.

Orbit arc length for the estimation is 1d. Seven successive daily solutions ensure more reliable results avoiding random anomalies. The reference atmosphere model, which is different from the original model in the simulation, is used to introduce systematic air drag errors. A more detailed set-up is presented in Table 1.

Empirical accelerations are usually used to compensate for force modelling errors. Empirical parameters in along- and cross-track directions are estimated per arc together with the initial orbit state vector of the satellites (Ge et al., 2020a; Kang et al., 2020). In each direction, one constant parameter and two 1-cycle-per-revolution (CPR) coefficients (sine and cosine term) are estimated. Besides initial state and empirical parameters, station (except first one as fixed) and satellite biases are also estimated. For the antenna pointing to the ground, a daily constant bias is estimated for each satellite and each station. While for the antenna used for ISL, one bias value is estimated for each pair of the linked satellites instead of two biases for the terminal of each satellite. The bias for a single ISL terminal cannot be estimated as only their sum is observable.

Table 1 Simulation and estimation settings

Orbit and data simulation		
Orbit height	900 km	
Walker constellation	73°: 90/9/1, as explained at the beginning of this section	
True force models	Earth gravity field	EIGEN 6S 60 × 60 (Förste et al., 2011)
	Air drag	DTM-2000 atmosphere model (Bruinsma et al., 2003)
Data time span	7 d (Oct 1–Oct 7, 2021)	
Sampling interval	1 min	
Elevation cut-off	10°	
Ground pseudorange	Noise level	5 mm (Michalak et al., 2021)
	Constant satellite bias	Random in the range ± 5 mm (1 terminal for each satellite) (Marz et al., 2021; Michalak et al., 2021)
ISL	Noise level	1 mm (Michalak et al., 2021)
	Constant satellite bias	Random in the range ± 5 mm per terminal (4 terminals for each satellite) (Michalak et al., 2021)
Estimation		
Arc length	1 d	
Initial state error	Random ± 3 mm for position, ± 3 μm/s for velocity	
Data weighting	Fixed weight with $\sigma_{range} = 5\text{mm}, \sigma_{ISL} = 1\text{mm}$	
Force models	Earth gravity field	EIGEN 6S 60 × 60
	Air drag	Modified Harris-Priester atmosphere model (Montenbruck & Gill, 2000, p. 89–91)
Parameters	Initial state vector, empirical accelerations per arc, and biases for each LEO satellite and station (as explained at the end of this section)	

Results

Influence of ground station distribution

Figure 2 shows 8 different ground networks selected for this study. Three regional networks located in Europe, China, and Brazil are chosen as the examples of local ground networks since they are located in different latitudes. By expanding these regional networks to a larger scope, we select three quasi-global networks, which are distributed along a latitude circle, and in different latitudes: high, middle, and low. For further comparison, we also select a quasi-global network that is distributed along a given longitude. At last, a global network is chosen. Each network contains 6 ground stations.

Individual satellite orbit solutions are compared to the simulated true orbits. Table 2 shows the mean RMS of orbit errors. Here, we introduce a new criterion called the best possible orbit, which will be denoted as "BPO" in the following figures. The best possible orbit is obtained by adjusting the true orbit based on the reference force models. The best possible orbit represents the best possible solution one can get with current modelling errors. More information about the best possible orbit can be found in Schlicht et al. (2020) and Marz et al. (2021). Figure 3 gives the 3D mean RMS of orbit errors for each satellite and the mean value for each simulation case without and with ISL. This figure reveals both averaged and scattered orbit errors. Moreover, the improvement of orbit accuracy with the help of ISL observations can also be seen from the figure.

As shown in Table 2, the along-track error dominates the orbit error. To show the influence of the station distribution, we first focus on the cases with only ground range observations. Figure 3 shows that the 3D mean RMS of orbit errors for regional networks are above 1 cm. For quasi-global networks, it is noticeable that orbit errors decrease to below 1 cm for middle and low latitude networks. Yet for the quasi-global network in high latitude, there are much larger errors in all three directions which lead to a much larger 3D orbit error than the other two quasi-global networks. This is due to the fact the high latitude network, as shown in Fig. 2 is close to the north pole and can be treated as a polar regional network. Therefore, compared with other quasi-global networks, this high latitude quasi-global network behaves like a regional network. Meanwhile, from Table 2, one may find that thanks to the better orbit determination in cross-track direction, the orbits from the longitude quasi-global network have an accuracy comparable to those from the low latitude quasi-global network. The longitude quasi-global network determines the orbits in cross-track direction at least 59% better than the latitude quasi-global network. With a global distribution of the ground station the orbit accuracy achieves its optimum. In general, with the same number of ground stations, as the stations are distributed more globally, the orbit errors decrease. The 3D mean

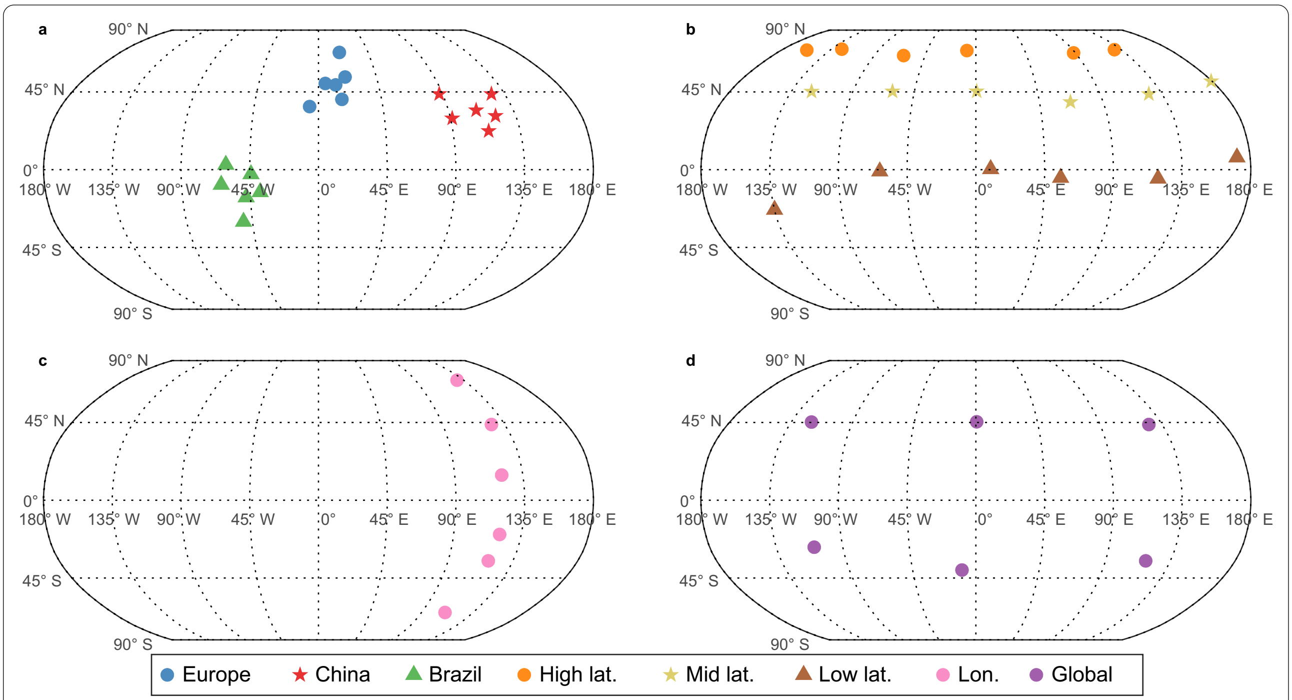

Fig. 2 Distribution of different ground networks: **a** regional, **b** quasi-global along latitudes, **c** quasi-global along longitude and **d** global

Table 2 Mean RMS of orbit errors in radial, along-track, cross-track and 3D position directions

Station network	Case	Mean RMS of orbit errors in radial direction (cm)	Mean RMS of orbit errors in along-track direction (cm)	Mean RMS of orbit errors in cross-track direction (cm)	Mean RMS of orbit errors in 3D position (cm)
Europe	Without ISL	0.58	1.99	0.92	2.36
	With ISL	0.11	0.54	0.16	0.59
China	Without ISL	0.49	1.65	0.66	1.89
	With ISL	0.11	0.56	0.20	0.62
Brazil	Without ISL	0.44	1.62	0.67	1.86
	With ISL	0.11	0.56	0.18	0.61
High lat	Without ISL	0.39	1.41	1.60	2.31
	With ISL	0.11	0.51	0.16	0.56
Mid lat	Without ISL	0.17	0.66	0.59	0.95
	With ISL	0.11	0.52	0.08	0.54
Low lat	Without ISL	0.17	0.63	0.63	0.95
	With ISL	0.11	0.52	0.09	0.55
Lon	Without ISL	0.24	0.75	0.24	0.84
	With ISL	0.11	0.52	0.10	0.54
Global	Without ISL	0.16	0.62	0.15	0.66
	With ISL	0.11	0.52	0.08	0.54
Median value	Without ISL	0.32	1.08	0.65	1.41
	With ISL	0.11	0.52	0.13	0.56
Best possible		0.11	0.51	0.01	0.52

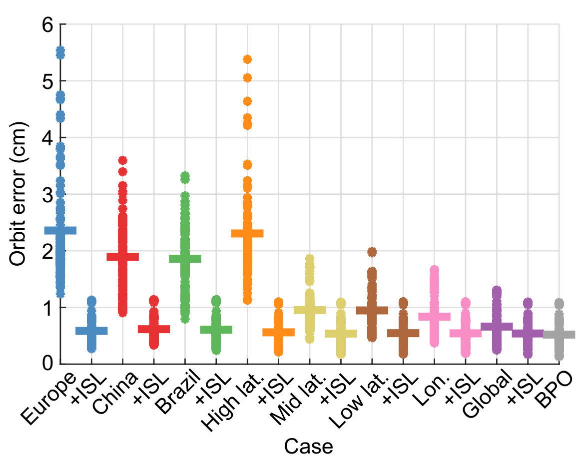

Fig. 3 3D mean RMS of orbit errors for each case. For each case, orbit errors of individual satellite are marked as stars and the mean of all satellites is marked as a bar. "+ISL" means that ISL observations are included in the estimation together with observations from the station network of the same color

RMS of orbit errors estimated with a regional network is improved by at least 49% when the network switches to quasi-global network (except high latitude quasi-global), and 65% to global one.

From another perspective, if the ISL observations are included in the estimation process, the orbit errors decrease in all cases. The 3D mean RMS of orbit errors for all cases are below 0.7 cm. For regional networks, ISL observations help improve the 3D orbit accuracy by about 70%. When a regional network expands to a broader region, the orbit improvement by adding ISL observations becomes smaller. The reason can be explained with the help of the best possible solution. The orbits determined with a global network only, not taking ISL observations into account, are already quite accurate: only about 0.14 cm worse than the solution of the best possible orbit. Due to the limitation by modelling errors, by adding ISL observations, the orbit errors reach the same level as the best possible solution and cannot be further reduced. For the same reason, since orbit errors in radial and along-track directions are reduced to the same level as the best possible solution with the help of ISL, there is little difference in these two directions when the network changes. It can also be observed that even for a regional network, adding ISL observations can reduce the orbit errors closely to the same level as the best possible solution. Moreover, from Fig. 3, one can observe that by adding ISL observations, the orbits determined using a regional network are even slightly better than for a global network without ISL observations. This is important since a global network is not always feasible. Although the orbit errors mainly occur in along-track direction due to the mismodelling, as shown by the best possible solution in Table 2, ISL can still help reduce errors in this direction to the same level as the best possible solution. Especially for regional networks, the orbit accuracy in along-track direction improves by at least 65%. In summary, to achieve precise orbits, for a regional station network, it is necessary to implement ISL; while for a global network, orbit determination also benefits from ISL observations.

It is worth to mention the importance of the geometry of the station distribution. The mean value of maximum gaps with no observations is longer than 600 min for regional networks but only around 150 min for a global network. This means that the global network can observe the satellites more frequently. A regional network, however, can only track a snippet of the daily arc due to its geometry limitation. This leads to a worse determination of the orbits. For additional insight in the quality of the solutions, Table 3 gives the mean formal errors of the 3D position of the initial state vector, as well as the average number of observations per day. All the cases here are the orbits determined with observations from ground station only. For comparison, the average number of ISL observations per day is about 260 000. Due to the poor geometry of the regional networks and the high latitude quasi-global network, their formal errors are at least 67% worse than for other networks. Since the inclination of the constellation is 73° and orbits converge is towards northern and southern latitudes, the satellites in the simulation always need to pass the polar regions every revolution, resulting in more observations for the stations in higher latitude. Taking the three latitude quasi-global networks as examples, the high latitude quasi-global network has much more observations than the other two networks. However, due to the poor geometry of the station distribution, this network leads to much worse orbits, as illustrated by Table 2 and Fig. 3. In other words,

Table 3 Formal errors of initial 3D orbit position and average number of observations per day, all cases are without ISL observations

Station network	Formal errors of initial 3D orbit position (cm)	Average number of observations per day
Europe	1.71	30,536
China	1.86	21,029
Brazil	2.16	16,974
High lat	1.72	44,507
Mid lat	0.63	24,725
Low lat	0.64	15,519
Lon	0.46	27,637
Global	0.32	21,556

for orbit determination, a network with better geometry distribution is more important than increasing the number of observations.

Besides orbit accuracy, the estimated bias accuracy is also analyzed. In general, ground range biases can be estimated to better than 0.6 mm, while the pair of ISL bias errors are below 1.5 mm. For bias estimation, although the station distribution still has an impact, the number of observations also plays a key role (Fig. 4). In order to investigate the necessity of on-ground satellite bias calibration, we further compare the orbit accuracy with and without biases. Table 4 gives the orbit errors determined with the observations from a global network with or without biases. For the cases with simulated biases, bias estimation is performed jointly with orbit estimation. For the cases without simulated biases, biases are

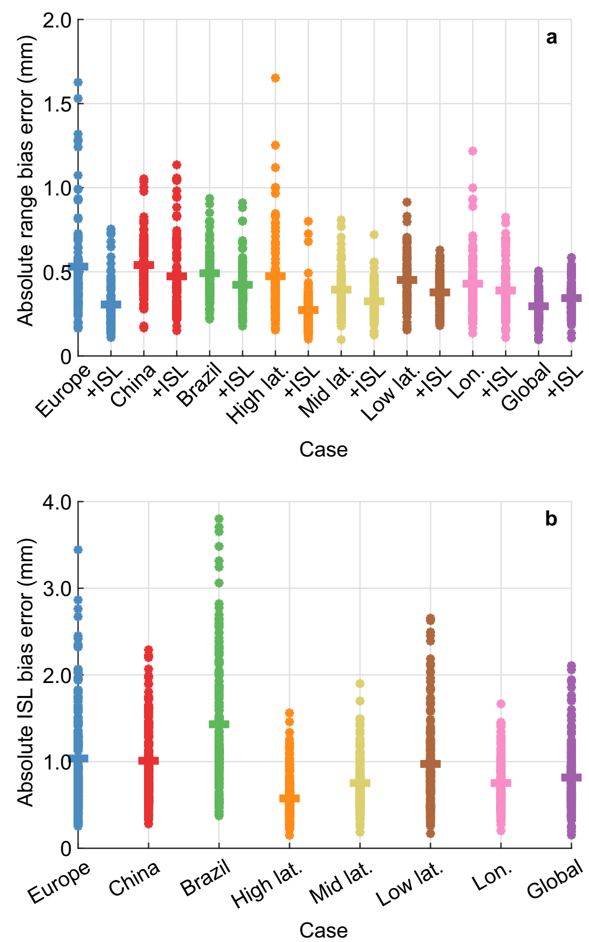

Fig. 4 Absolute bias errors for each case. Top: absolute ground range bias errors; bottom: absolute ISL bias errors (per pair). For each case, bias errors of individual satellites (for ground range biases) and each pair of satellites (for ISL biases) are marked as stars and the mean of all biases is marked as a bar. "+ISL" means that ISL observations are included in the estimation together with observations from the station network of the same color

Table 4 Mean RMS of orbit errors in radial, along-track, cross-track and 3D position directions, global network

Case		Mean RMS of orbit errors in radial direction (cm)	Mean RMS of orbit errors in along-track direction (cm)	Mean RMS of orbit errors in cross-track direction (cm)	Mean RMS of orbit errors in 3D position (cm)
With biases and bias estimation	Without ISL	0.16	0.62	0.15	0.66
	With ISL	0.11	0.52	0.08	0.54
No biases and no bias estimation	Without ISL	0.17	0.62	0.15	0.67
	With ISL	0.11	0.51	0.07	0.53
Best possible		0.11	0.51	0.01	0.52

not estimated. Obviously, with bias estimation, the orbit errors can reach the same accuracy level as for the case without biases in the observations. Therefore, for the purpose of estimating precise orbits, a precise pre-launch satellite bias calibration is not necessary if the biases are estimated during the orbit determination process.

Influence of number of ground stations

Having discussed the influence of the station distribution, we now focus on another factor that might impact the accuracy of orbit determination: the number of ground stations. It is interesting to find a proper number of ground stations to reach the best cost performance. Figure 5 gives five ground networks with different number of stations, from 1 to 60 stations.

Figure 6 displays the mean RMS of orbit errors for the four networks (except 1-station network) with and without ISL observations in addition to the ground stations. The error bars represent the Standard Deviations (STD) of these RMS orbit errors over 7 days. Table 5 gives the values in detail. Without ISL observations the orbits improve as the number of ground stations grows. The 3D mean RMS of orbit errors decrease from about 98% (1-station to 6-station) to even no changes (32-station to 60-station). The improvement of orbits by increasing the number of stations becomes less attractive when the number is larger than 16.

With the ISL observations, it is also clear that the orbits benefit a lot. Especially for the 1-station case, orbit errors in radial and along-track directions decrease to the same level as the best possible solution. The 3D mean RMS of orbit errors of the 1-station network decrease by 98% and is only 0.1 cm larger than the best possible solution, which is even better than the solution for the 6-station network without ISL observations. By increasing the number of stations, the 6-station case with ISL observations has the same orbit accuracy as a 32- or even 60-station case. This shows the great advantages of ISL observations for a small network.

General comparison in terms of the distribution and number of ground stations

Having discussed the influences of station distribution and number of stations separately, we now consider a general case: the comparison of orbit errors when using a regional network with large number of stations and a global network with only few stations. We choose the European network as an example. Figure 7 displays four European regional networks with various numbers of stations. For comparison, station numbers stay the same in the global networks of Fig. 5.

Table 6 and Fig. 8 present the mean RMS of orbit errors for the European and global regions with different number of stations. Without ISL observations, the orbit gradually improves with the increase of the number of stations in both networks, but the rate gets smaller and there is no significant improvement when the number of stations is larger than 16. This is consistent with the discussion in the Sect. "Influence of number of ground stations". Without the ISL observations, in radial, along- and cross-track directions, even a European network with 60 stations performs much worse than a global network with 6 stations. The 3D mean RMS of orbit errors is about 1.7 times larger for the 60-station regional network. This also proves that the geometric distribution of the stations is more important, which is mentioned earlier in Sect. "Influence of ground station distribution".

By adding ISL observations, the orbit errors can be largely reduced for the regional European network. The 3D mean RMS of orbit errors decrease from centimeter level to less than 0.6 cm. For a regional network with 6 stations, the orbit errors can be even slightly lower than for a global network without ISL observations. With ISL, a network with 6 stations is enough to determine the orbits, close to the best possible solution. From Table 6, it is noticeable that unlike a global network, a regional network with ISL observations cannot further reduce orbit errors by adding more stations. There is a 12% error gap compared to the best possible solution. The geometric

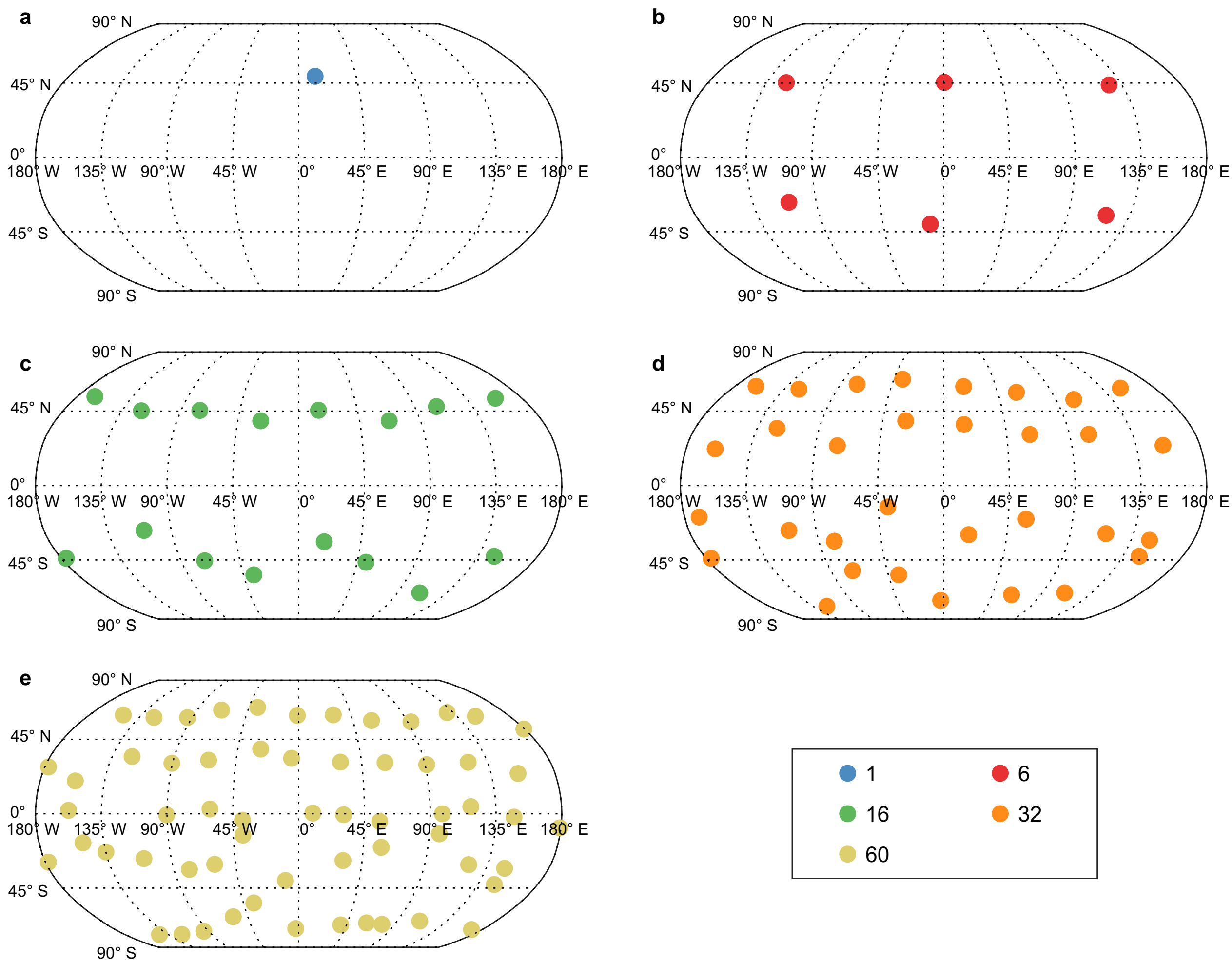

Fig. 5 Distribution of different number of ground stations for global networks: **a** 1, **b** 6, **c** 16, **d** 32 and **e** 60

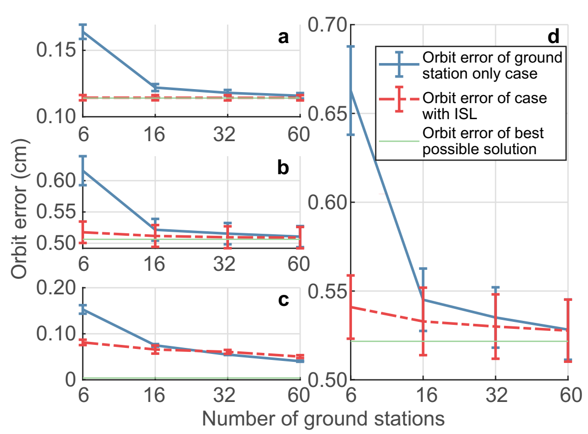

Fig. 6 Mean RMS of orbit errors with respect to the number of ground stations in **a** radial, **b** along-track, and **c** cross-track directions and **d** 3D position for global networks. Note in different scales

limitation of the station distribution is responsible for this remaining error.

In summary, for a regional network, increasing the number of stations can help reduce orbit errors, but the gains are not competitive compared to the solution from a global network. Establishing ISL between satellites is more favorable since it can help reduce orbit errors greatly, close to those from the solution of a global network.

Conclusions and outlook

In this study, we analyze the impact of different ground networks and ISL observations on the orbit determination of a LEO satellite constellation. The simulations are simplified yet considering basic errors such as force model errors, instrumental errors as well as measurement errors.

In the first part, we show the influence of the ground station distribution on the determined orbit. Three

Table 5 Mean RMS of orbit errors in radial, along-track, and cross-track directions, and 3D position for a global network

Number of stations	Case	Mean RMS of orbit errors in radial direction (cm)	Mean RMS of orbit errors in along-track direction (cm)	Mean RMS of orbit errors in cross-track direction (cm)	Mean RMS of orbit errors in 3D position (cm)
1	Without ISL	6.48	28.99	25.19	40.79
	With ISL	0.11	0.56	0.22	0.62
6	Without ISL	0.16	0.62	0.15	0.66
	With ISL	0.11	0.52	0.08	0.54
16	Without ISL	0.12	0.52	0.07	0.55
	With ISL	0.11	0.51	0.01	0.53
32	Without ISL	0.12	0.52	0.05	0.54
	With ISL	0.11	0.51	0.05	0.53
60	Without ISL	0.12	0.51	0.04	0.53
	With ISL	0.11	0.51	0.04	0.53
Median value	Without ISL	0.12	0.52	0.07	0.55
	With ISL	0.11	0.51	0.05	0.53
Best possible		0.11	0.51	0.01	0.52

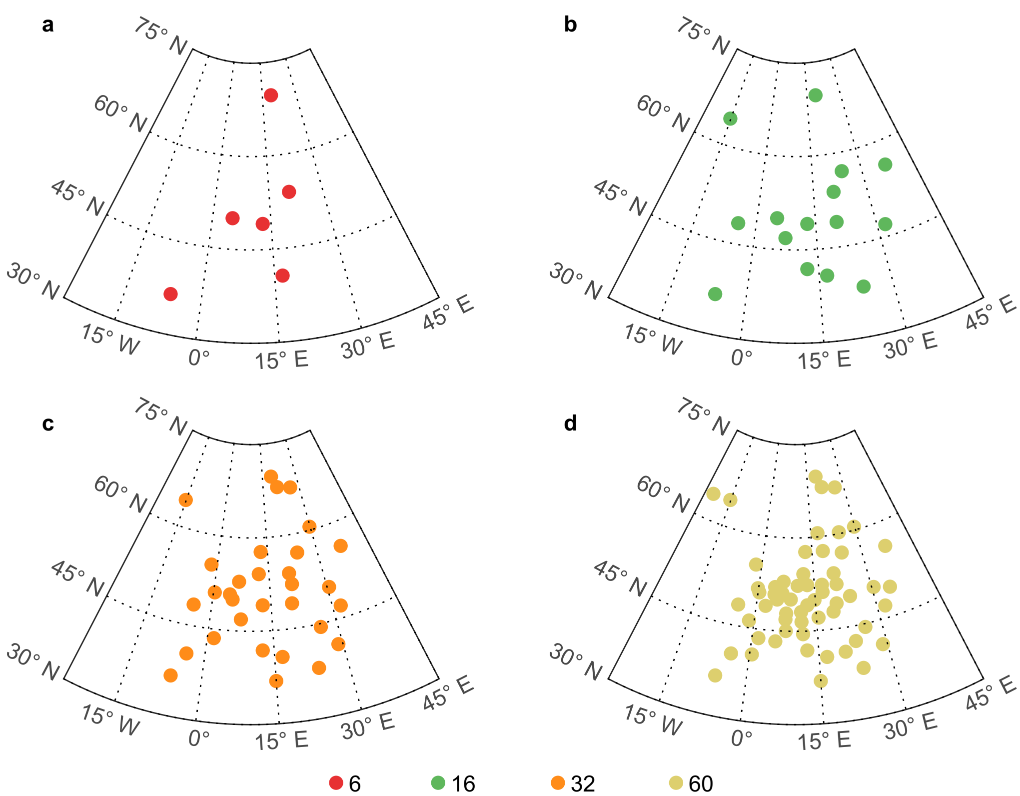

Fig. 7 Distribution of European regional networks with different number of ground stations: **a** 6, **b** 16, **c** 32 and **d** 60

regional networks, four quasi-global networks as well as a global network with 6 ground stations are defined. The results show that, as expected, the orbit errors get smaller with a more global network. A high latitude network leads to larger orbit errors than a low or middle latitude network due to its poor geometry. Compared to the number of observations, the geometry of the ground station distribution is more important when it comes to

Table 6 3D mean RMS of orbit errors for the networks with different number of stations

Station distribution	Case	3D mean RMS of orbit errors for 6 stations (cm)	3D mean RMS of orbit errors for 16 stations (cm)	3D mean RMS of orbit errors for 32 stations (cm)	3D mean RMS of orbit errors for 60 stations (cm)	Median value (cm)	Best possible (cm)
Global	Without ISL	0.66	0.55	0.54	0.53	0.55	0.52
	With ISL	0.54	0.53	0.53	0.53	0.53	
Europe	Without ISL	2.36	1.73	1.72	1.75	1.74	
	With ISL	0.59	0.59	0.59	0.59	0.59	

orbit determination. By adding ISL observations to those networks, it is demonstrated that orbit errors get comparable to the best possible solution for all networks. It is noteworthy that the orbit errors from a regional network with ISL observations can be smaller than those for a global network without ISL observations. Meanwhile, the analysis of estimated biases indicates that, like for orbit estimation, station distribution also plays an important role in bias estimation. In addition, the number of observations is another key to improve satellite bias accuracy. We further prove that to estimate precise orbits it is not necessary to precisely calibrate satellite biases on ground. The results show that in our simulation (6 global stations with/without ISL), by estimating bias parameters together with orbital parameters, the orbit accuracy can be as accurate as for the case without any biases in the observations.

We also conduct experiments on the relationships between the number of stations and orbit errors. We chose five global networks containing different number of stations from only 1 station to a maximum of 60 stations. When orbits are determined using the observations only from ground stations, with more stations, the orbit improvement rate becomes smaller. Orbit accuracy does not benefit much from more than 16 stations.

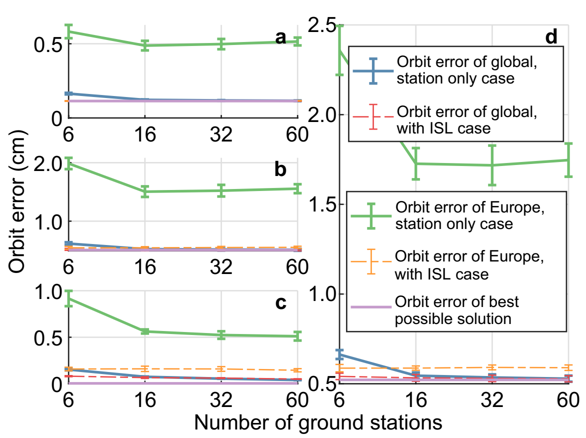

Fig. 8 Mean RMS of orbit errors with respect to the number of ground stations for 2 regions in **a** radial, **b** along-track, **c** cross-track directions and **d** 3D position. Note in different scales

Meanwhile, ISL observations can also help reduce orbit errors, especially for a network with few stations. The orbits determined using a 6-station network with ISL observations can almost be as accurate as for a 60-station network.

In the last part, four European networks are selected to represent different number of stations in a regional network. The simulation results prove that by increasing the station number in one region alone, the orbits are not improved much. A solution with 60 stations in Europe is worse than a global network with just 6 stations. With the help of ISL observations, orbit errors are at the same level as the solutions from global networks.

This contribution focuses on the station network analysis. In the future we are going to assess more realistic quality indicators of satellite orbits. With the further development of our new software, more systematic errors will be included in the simulation, so that it will be closer to reality. Meanwhile, the model in the estimation can also be further improved. For instance, the empirical acceleration model can also be replaced by a piece-wise constant acceleration model. Finally, it would also be interesting to see how different ISL topologies will affect the performance of orbit determination.

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Author contributions
X.H. and Y.N. proposed the idea. X.H., U.H. and A.S. designed the experiment. X.H. developed the software, carried out the simulations and drafted the article. B.D. assisted in paper writing and revision. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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